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16. Abstract

The objective of this study was to perform a data-driven assessment of various aspects of the helicopter structural usage monitoring process and to identify key issues and requirements that must be addressed prior to using the monitoring information for part life extensions or maintenance credits. Structural usage monitoring is defined in this report to be the identification of the aircraft usage spectrum flight regimes for any given instant in the aircraft or component life. With this aircraft maneuver, or regime information, the fatigue damage accumulation on helicopter components can be tracked. The ultimate goal of a structural monitoring system is to produce more insight into exactly how an aircraft is being used once it is fielded. This information can be compared to design assumptions and then part life extensions (or reductions) can potentially be granted.

During this study, several structural monitoring system design issues are addressed, including the types of aircraft parameters to be monitored, the data rates at which those parameters should be monitored, as well as a recommended algorithm development and validation approach. The results of this report set the recommended basic design criteria for developing a reliable regime recognition software module for commercial as well as military rotorcraft.

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EXECUTIVE SUMMARY

The objective of this study was to perform a data-driven assessment of various aspects of the helicopter structural usage monitoring process and to identify key issues and requirements that must be addressed prior to using the monitoring information for part life extensions or maintenance credits. Structural usage monitoring is defined in this report to be the identification of the aircraft usage spectrum flight regimes for any given instant in the aircraft or component life. With this aircraft maneuver, or regime information, the fatigue damage accumulation on helicopter components can be tracked. The ultimate goal of a structural monitoring system is to produce more insight into exactly how an aircraft is being used once it is fielded. This information can be compared to design assumptions and then part life extensions (or reductions) can potentially be granted.

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1. INTRODUCTION.

Helicopter Health and Usage Monitoring Systems (HUMS) are a combination of sensors, data acquisition technology, and software algorithms (both onboard and ground-based) that are provided as a unit with the goals of reducing maintenance costs and improving safety. In general, a multifunctional HUMS system consists of one or more of the following functionalities: rotor track and balance, exceedance monitoring, engine and drive train diagnostics, and structural usage monitoring. This report will focus on assessing the requirements for structural usage monitoring only.

In this report, the term structural usage monitoring refers to the process of recognizing the flight regime flown by an individual aircraft at a given time. A listing of flight regimes applicable to commercial aircraft that should be able to be identified by a HUMS is listed in appendix A. The measured usage spectrum for any given aircraft can then be mapped to particular components on that aircraft. Components that are used less severely than previously assumed could see some beneficial life extension. Likewise, components flown more severely than previously assumed could be removed and replaced early, thus improving flight safety. This process of life extension (or penalty) based on structural usage monitoring data is known as the application of maintenance or usage credits and will be referred to as such in this report. The application of maintenance credits is a prime motivation for investing in HUMS systems.

As such, a methodical analysis of process requirements is necessary before a maintenance credit program can be implemented. This report will focus on the key aspects of designing and developing a reliable structural usage monitoring (also known as regime recognition) module. The process of mapping this information to individual aircraft components, as well as the necessary data integrity checks that must be in place, will be covered in a separate report.

2. PARAMETER SET EVALUATION.

A number of different types of systems have been used by the Navy to conduct rotary wing structural monitoring programs. Some of the early systems were actually fixed wing monitoring systems modified to perform the rotary wing monitoring function. Other systems, and certainly the later ones, were designed specifically for rotary wing applications. Some systems were specifically fielded to perform the structural usage monitoring function only, while other helicopter systems such as the V-22, H-60, and H-53 have multifunctional HUMS. However, all the systems use the same basic approach to performing the structural monitoring function. They all monitor various aircraft state parameters, and that information is used to identify the operating maneuver that the aircraft is in at any given time.

2.1 CORE PARAMETER SET.

The number and types of parameters monitored for Navy structural monitoring applications have varied, depending on the particular aircraft's databus capabilities and when the system was fielded. The parameters necessary for regime recognition have been separated into three groups: a core set of required parameters, a required set of aircraft configuration specific parameters (table 1), and a set of useful but not absolutely necessary parameters, which have been found to be useful in improving regime recognition reliability when they are available. These parameters are likely to be available on an aircraft with more modern database capability such as the V-22.

TABLE 1. CONFIGURATION-SPECIFIC PARAMETERS FOR DIFFERENT AIRCRAFT MODELS

Configuration-Specific Parameters	V-22	H-53	H-60	AH-1Z	UH-1Y
Blade fold	X	X	X	X	X
Sling load	X	X			X
Aerial refuel	X	X			
Wing stow	X				
Landing gear position	X				
Nacelle angle	X				
Rotor brake		X	X	X	X
Pylon fold		X			
RAST*			X		
Armament configuration				X	

*RAST–Recovery, Assist, Secure, and Traverse

2.1.1 Core Structural Monitoring Parameters.

- Airspeed
- Pitch attitude
- Roll attitude
- Pitch rate
- Roll rate
- Yaw rate
- Vertical acceleration
- Vertical velocity
- Engine torque
- Weight on wheels
- Rotor speed
- Fuel quantity
- Pilot stick positions
- Altitude
- Outside air temperature
- Gross weight
- Rotor brake

2.1.2 Useful Structural Monitoring Parameters.

- Heading
- Lateral acceleration
- Long acceleration
- Ground speed
- Ground track
- Radar altitude
- Swashplate tilt
- Rotor torque
- Parking brake
- Rotor flapping

Maximum use of pre-existing aircraft parameters is recommended wherever possible, as opposed to dedicated sensors for structural monitoring only. This will ensure higher levels of system operation since these transducers must be operational to fly the aircraft. In contrast, dedicated structural monitoring sensors might not be expeditiously repaired.

2.2 EFFECT OF REDUCED PARAMETER SET.

In addition to determining the generic set of parameters that are necessary to recognize regimes, an assessment was also done to identify the parameters that could be monitored to get the majority of the regime information necessary to track fatigue damage on key components. This evaluation was done using H-60R damage tables.

First, four key parameters must always be monitored: gross weight, altitude, outside air temperature, and airspeed. These are prorate parameters that are used in all regimes for establishing time spent in high gross weight, high-altitude, and high-speed conditions. If only two parameters are added to this parameter set, rotor speed and weight on wheels, then ground-air-ground (GAG) cycles can be recognized. GAG cycles are dominant contributors to damage accumulation for many components. For the SH-60R, figure 1 shows that by recognizing GAG cycles only (six parameters total), 75% of the fatigue damage can be tracked for over 20% of the life-limited components. Table 2 shows the key parameters that can be added, along with the associated regime that can be recognized by carrying those parameters. Figure 1 shows the effect these parameters have on the number of components that can be tracked for fatigue damage accumulation. For example, by monitoring the top eight parameters listed in table 2, 75% of the fatigue damage can be monitored for 38% of the components. If all 14 of the parameters in table 2 are monitored, then 100% of the damage can be tracked for 66% of the components of interest.

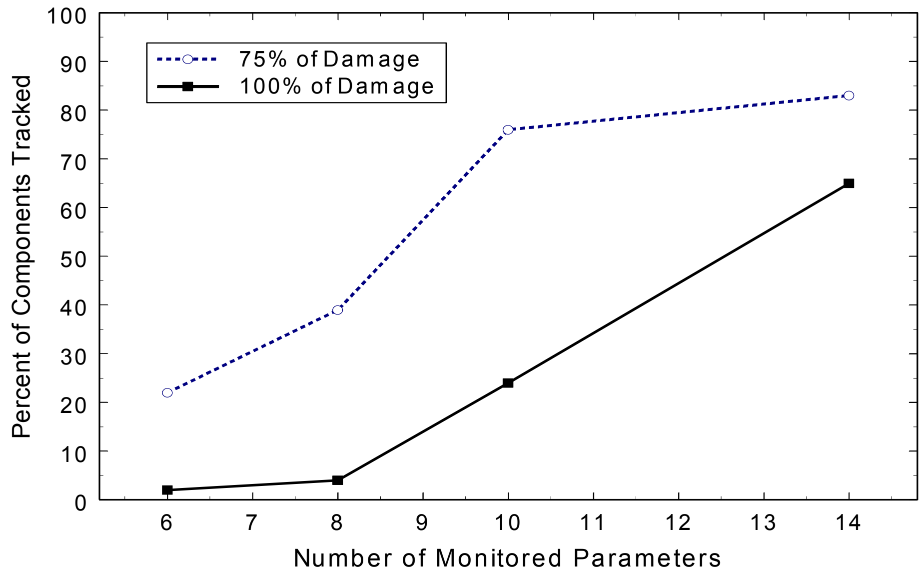

FIGURE 1. SH-60R PARAMETER-BASED COMPONENT DAMAGE ASSESSMENT

TABLE 2. PARAMETERS MONITORED AND CORRESPONDING MANEUVER RECOGNIZED

Total Parameters	Parameter Monitored	Maneuver Identified
1	Gross weight	Prorating parameters needed for all regimes.
2	Altitude	
3	Outside air temperature	
4	Airspeed	
5	Rotor speed	GAG cycles with and without rotor start.
6	Weight on wheels	
7	Vertical velocity	Turns, dives, descents
8	Roll angle	
9	Pitch rate	Pullups
10	Vertical acceleration	
11	Collective stick position	Control reversals
12	Lateral cyclic stick position	
13	Longitudinal cyclic stick position	
14	Pedal position	

While this damage assessment is specific to the H-60R, the maneuvers that are typically damaging in a military spectrum are GAG cycles, turns, pullups, and sometimes, control reversals. It is expected that these are also the driving maneuvers for a commercial aircraft spectrum. So, in terms of the key parameters used, this analysis is fairly generic and these parameters will likely be the key parameters for other aircraft models as well. The components that are not covered with this limited parameter set could be tracked by conventional means (e.g., pilot-reported flight hours) if there were no viable means to measure the additional parameters necessary to track those components. This assessment can also be tailored to determine which parameters are necessary to track the damage on a particular component, say the shortest life component or the most expensive component. A tradeoff in logistic benefit versus cost of the monitoring system could then be performed to determine the optimal solution for the specific aircraft model.

3. PARAMETER DATA RATE EVALUATION.

In addition to identifying the key parameters necessary to perform regime recognition, the rate at which the regime algorithm must operate is also very important. The rate at which the algorithm operates is driven by how quickly the input parameters change. Parameters must be monitored and recorded at the appropriate rate to ensure that peak information is captured properly and to ensure that the usage monitoring results are accurate. To illustrate the importance that data rate has on recognition success, refer to figure 2.

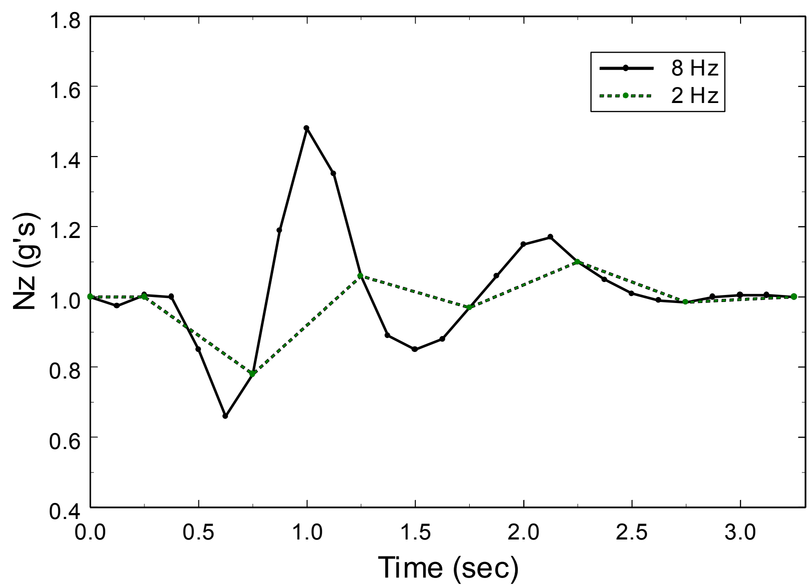

FIGURE 2. EFFECT OF DATA RATE ON VERTICAL ACCELERATION

Figure 2 shows the effect of monitoring vertical acceleration, Nz, at 2 Hz (dotted line) and at 8 Hz (solid line). At 8 Hz, it can be seen that the peak Nz value is about 1.5 g. However, when the same signal is monitored and recorded at 2 Hz, the peak information is totally missed. Therefore, if regime recognition is processed at 2 Hz or lower, a pullup would not be recognized as the maneuver flown, and the damage associated with that pullup would not be accounted for.

Likewise, if the sample rate for Nz is increased slightly to 4 Hz, the peak Nz value would still not be detected. In this instance, the regime recognition algorithm may actually identify the maneuver flown as a pullup, but the severity of the pullup would be in error. The Nz detected for the maneuver will be less than the actual Nz, producing an erroneous underassessment of the fatigue damage associated with the maneuver.

Similarly, if roll attitude is monitored at an inadequate data rate, then peak roll angle information will be missed. This inadequate data rate would likely result in the turn being identified, but the severity of the turn being misclassified. The effect of not properly capturing the severity of a turn can, over time, be very significant in a fatigue damage assessment. Figure 3 illustrates this point for two H-60 components.

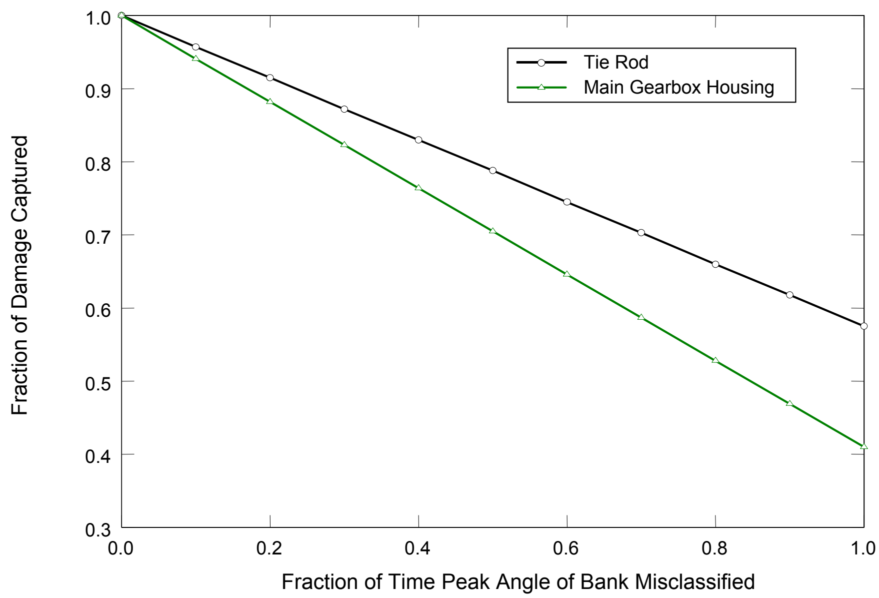

FIGURE 3. EFFECT OF MISCLASSIFYING A 45° ANGLE OF BANK TURN AS A 30° ANGLE OF BANK TURN

On the x axis of figure 3 is the fraction of time that a 45° angle of bank (AOB) turn is misclassified as a 30° AOB turn, and on the y axis is the fraction of damage that is accurately captured. For example, for the tie rod, if 0.5 of the time the severity of the turn is not captured properly, then that component would nominally accrue only 0.79 of the actual damage. For the main gearbox housing, only 0.70 of the damage would be accurately captured for a 0.5 misclassification.

For the data shown in figures 2 and 3, in both cases, the result of the inadequate data rate would be a nonconservative life extension. Clearly, the data rate is important in establishing the reliability of a usage monitoring system. As a result of this criticality, a comprehensive examination of each input parameter of interest was performed to determine the minimum data rate where peak information and regime recognition results are not adversely affected. An investigation of this nature, however, is only as good as the data used in the study. For this reason, two comprehensive data sets were used: the SH-60B and the MV-22 flight load survey databases. These databases include all spectrum maneuvers flown at various gross weights and center of gravity (c.g.) configurations to qualify the aircraft structurally. As such, it is believed that the data rates established in this report encompass important high-load maneuvers and worst-case aircraft configurations for a multimission utility helicopter as well as for a tiltrotor aircraft. Results from this analysis cannot necessarily be applied to a fighter or attack type of helicopter, which may have greater data rate requirements due to the inherent agility of an attack helicopter. However, this limitation has no impact on this Federal Aviation Administration (FAA) study since there is no commercial application for a fighter or attack helicopter.

The data rate study was performed by comparing an original signal to a down-sampled signal and noting the maximum difference between the two cases. The down-sampled signal was interpolated to the original data rate such that an error value could be calculated for every original data point. For example, referring again to figure 2, the maximum error between the 8-Hz signal and the 2-Hz signal, which occurs at 1 sec, is approximately 0.55 g. An error is calculated for every point of the original data rate and a maximum error value is determined that corresponds to the worst-case discrepancy in the data set. This process is then repeated for a series of different data rates to assess error trends.

The criteria for establishing a maximum acceptable error for a given parameter depends on several factors. First, the sensitivity of the regime algorithm to a specific parameter must be assessed. For example, the regime recognition algorithms are not particularly sensitive to altitude. A turn can be identified just as well at 1000 ft as it can be at 2000 ft. But, regime algorithms are quite sensitive to Nz. If Nz is greater than 1.15 g or less than 0.85 g, then the regime recognition algorithm will trip into a nonlevel flight regime.

A second factor that is important in establishing maximum acceptable errors is the fidelity of the loads data associated with a given parameter. Again using altitude as an example, loads data are typically gathered at three to four different altitude bands with wide altitude ranges within each altitude band. For example, one altitude band is sea level, which is typically defined as any altitude between 0 and 3000 ft. A parameter with more fidelity in terms of its associated loads data is AOB or roll attitude. Loads data are typically collected at 30°, 45°, and 60° AOB. For regime recognition purposes, a turn that is recognized between 10° and 35° AOB would likely be mapped to the fatigue damage associated with a 30° turn, whereas a turn that is recognized between a 35° and a 50° AOB would be mapped to the fatigue damage associated with a 45° AOB turn. While the AOB bands may appear relatively large (10° to 35° and 35° to 50°), a high degree of accuracy is necessary around the break points (35° in this case) to ensure that the recognized regime is mapped to the appropriate damage fraction. If the data rate is not sufficient, then a 45° AOB turn will be misclassified as a 30° AOB turn and fatigue damage accumulation will be missed. This is shown in figure 3.

Figure 4 shows the trend of maximum error versus data rate for Nz for the H-60 and the V-22. As expected, the error decreases as the data rate is increased. Examination of figure 4 shows that beyond 6 Hz, the decrease in maximum error is minimal. Also of note in this figure is that the V-22 generally had lower error values than the H-60. This is due primarily to a slightly noisier signal in the H-60 data that is most likely due to the different signal-conditioning techniques used by the onboard data acquisition systems. The maneuvers associated with the maximum errors were rolling pullup maneuvers for the V-22 and symmetric pullups and control reversals for the H-60. The recommended data rate for Nz is 7 to 8 Hz. By using the recommended data rates (or anything higher), all pullup maneuvers will be recognized and the chances of misclassifying the severity of a pullup maneuver will be low enough to preclude any significant unaccounted fatigue damage accumulation.

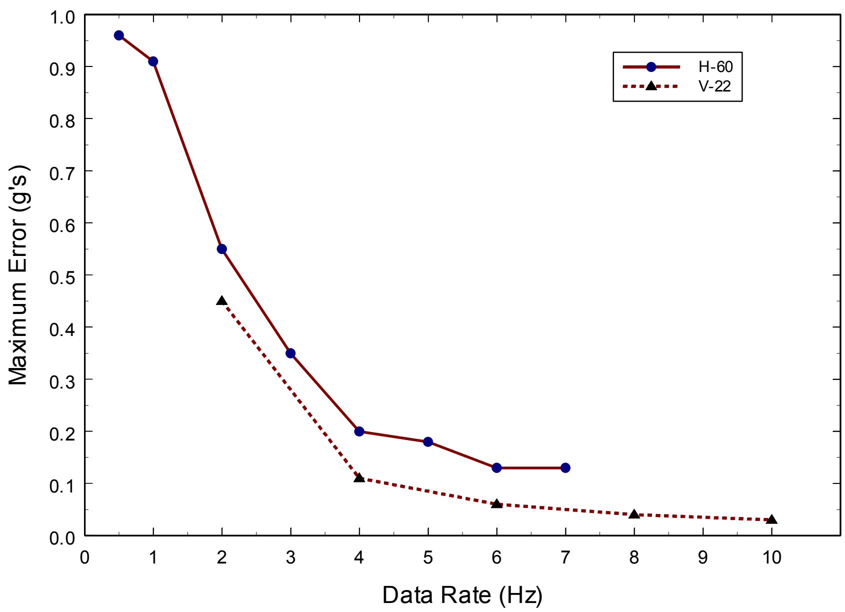

FIGURE 4. MAXIMUM ERROR TRENDS FOR VERTICAL ACCELERATION

3.1 MILITARY SPECTRUM DATA RATES.

A summary of minimum acceptable data rates for each parameter is shown in table 3 along with the associated maximum error. In the baseline calculations, all available flight data were used to establish the minimum acceptable data rate. However, there were a few parameters where further data review was necessary to ensure that this data rate was appropriate. For example, the maneuver corresponding to the maximum error for rotor speed is a symmetric pullup. A data rate of 6 Hz is required to accurately capture the minimum and maximum values associated with rotor overspeeds and underspeeds that can occur during transient maneuvers. However, if rotor speed is only being monitored for the purposes of identifying rotor starts and stops, as is often the case, then a 1-Hz data rate would be sufficient to monitor rotor speed.

For lateral and longitudinal accelerations, the maneuvers driving the worst-case errors are transient maneuvers. However, longitudinal and lateral accelerations are typically used for recognition of maneuvers such as level flight, accelerations, decelerations, and sideslip maneuvers. When only these flight maneuvers are included in the data set, minimum data rates of 4 Hz for longitudinal acceleration and 1 Hz for lateral acceleration are acceptable. The parameters listed in tables 1 and 2 and in section 2.1.1 that are not listed in table 3 can be recorded at 1 Hz with sufficient accuracy. Discrete parameters such as weight on wheels or rotor brake can be recorded only when a change of state occurs or at 1 Hz, whichever is more convenient.

TABLE 3. DATA RATES REQUIRED TO CAPTURE PEAK INFORMATION FOR A MILITARY SPECTRUM

Parameter	Data Rate (Hz)	Max Error
Rotor speed	6	0.83%
Vertical acceleration	8	0.13 g
Pitch attitude	2	1.8°
Roll attitude	4	2.0°
Pitch rate	4	3.0°/sec
Roll rate	8	2.8°/sec
Yaw rate	4	2.5°/sec
Airspeed	2	4.3 kt
Engine torque	6	3% error
Longitudinal stick position	6	3.1%
Lateral stick position	6	3.9%
Collective stick position	5	3.4%
Pedal position	6	3%
Long accel	6	0.03 g
Lateral accel	7	0.05 g
Radar altitude	2	13 ft
Vertical velocity	8	242 fpm
Longitudinal flapping	8	0.61°
Lateral Flapping	8	1.0°
Lateral swashplate tilt	8	1.1°
Longitudinal swashplate tilt	8	1.5°

3.2 LEVEL FLIGHT DATA RATES.

Table 3 provides the data rates necessary to capture peak information properly and to assure that no maneuvers are missed due to inadequate data rate. The results in table 3 apply to the entire spectrum of regimes that would be recognized for military-type aircraft. The maximum errors in table 4 are typically driven by transient maneuvers such as pullups or control reversals. However, for steady-state maneuvers like level flight, the data rate requirements are reduced. For a system where continuous parameter data are being recorded, it may be desirable to record at a reduced data rate during level flight maneuvers to minimize data storage requirements. For this type of approach, all parameters would still be sampled at the high data rates established in table 3, except when a level flight condition is recognized by the onboard system. A reduced data recording rate could then be used. It was determined through review of level flight data that 1-Hz data recording is sufficient during level flight. However, pilot stick and pedal positions need to continue to be recorded at the rates stated in table 3 due to the fact that control reversals can occur during level flight. For the purposes of regime recognition, level flight can be defined as those flight conditions where rate of climb is within ±500 fpm, roll attitude is within ±10°, and Nz is less than 1.15 g but greater than 0.85 g.

TABLE 4. DATA RATES REQUIRED TO CAPTURE PEAK INFORMATION FOR A COMMERCIAL SPECTRUM

Parameter	Data Rate (Hz)	Max Error
Rotor speed	2	1.53%
Vertical acceleration	6	0.13 g
Pitch attitude	2	1.7°
Roll attitude	4	2.0°
Pitch rate	3	3.0°/sec
Roll rate	6	3.6°/sec
Yaw rate	4	2.5°/sec
Airspeed	2	4.3 kt
Engine torque	6	2.9%
Longitudinal stick position	5	3.2%
Lateral stick position	6	3.9%
Collective stick position	4	4%
Pedal position	6	3%
Long accel	5	0.03 g
Lateral accel	7	0.05 g
Radar altitude	2	12 ft
Vertical velocity	6	243 fpm
Longitudinal flapping	2	0.5°
Lateral Flapping	1	0.8°
Lateral swashplate tilt	2	1.0°
Longitudinal swashplate tilt	2	1.1°

3.3 COMMERCIAL SPECTRUM DATA RATES.

The results in table 3 represent the data rates required to recognize all flight maneuvers in a military usage spectrum. For these results to be most useful for the FAA, maneuvers which were deemed military only were removed from the data set, and the required data rates were reassessed. Examples of typically fatigue-damaging, military-specific maneuvers include rolling pullups, windup turns, and gunnery turns. The maneuvers that remain in the data set are then representative of commercial maneuvers. The required data rates associated with these maneuvers are listed in table 4. The maximum errors in table 4, as in table 3, are typically driven by transient maneuvers such as pullups or control reversals. Comparison of tables 3 and 4 show that there is little significant change in data rate requirements between the military and commercial spectrums using the H-60 and V-22 aircraft data.

4. REGIME RECOGNITION ALGORITHM DATA RATES.

Once data rates for individual regime recognition input parameters have been established, the appropriate data rate at which the regime algorithm should be processed can be established. For the military spectrum, using only the required parameters listed in table 1 and section 2.1.1, the minimum data rate is driven by vertical acceleration, roll rate, and vertical velocity. These parameters are critical in accurately identifying symmetric pullups, rolling pullups, and climbs and dives. So the regime recognition algorithm computation rate for a military spectrum (not including attack-type helicopters) is 8 Hz. This data rate will ensure that high-g maneuvers are assessed with the appropriate amount of time in maneuver, and the appropriate g-level is captured.

For level flight, with the exception of pilot stick and pedal positions, the recommended data rate is 1 Hz. With this data rate, the time spent in level flight (and the associated airspeed) can be captured to within 1 second of accuracy for any given instance. However, the stick positions and pedal positions must continue to be monitored and recorded at the high rate of 6 Hz to ensure that control reversals can be reliably recognized.

For the commercial spectrum, obtained with aggressive, military-specific maneuvers removed, there is a slight decrease in the data rate requirements. A 6-Hz processing rate is necessary. This data rate is driven by vertical acceleration, roll rate, vertical velocity, and engine torque. Depending on how these parameters are used in the specific regime algorithms that are developed, it may be desirable to operate at a reduced data rate for a specific parameter. Plots of maximum error trends with data rate are provided in appendix B for key high-rate parameters. These plots should allow for further evaluation of the tradeoff of maximum error with data rate for the specific commercial application.

5. ALGORITHM DEVELOPMENT AND VALIDATION.

Once parameters and data rates for the regime recognition system have been established, the specific regime algorithm must be developed. The development of regime recognition algorithms requires the use of an extensive flight test database that includes time history data of all spectrum maneuvers, i.e., all the maneuvers that the aircraft is expected to fly during operation. If the flight database for the original aircraft qualification testing is available, and the appropriate parameters and data rates were recorded in time history form, these data can be used for algorithm development. If these data are not available, then a dedicated algorithm development flight test program is necessary. For an algorithm development flight test program, each spectrum maneuver must be flown several times with several different pilots to ensure that the algorithms that are developed account for pilot and maneuver variability. It is recommended that the maneuvers be flown three times with three different pilots for a total of nine repeated flights of all spectrum maneuvers.

During the development phase, it is most efficient to use recorded flight data in conjunction with a ground-based set of regime recognition algorithms. Incorporating the regime recognition algorithms in the onboard system at this stage is not recommended. It is much more efficient to collect all the necessary flight data once and adjust the regime recognition algorithms on the ground. The recorded data can be replayed through the algorithms as many times as necessary to optimize the regime recognition reliability. This approach is much less costly and time consuming than reflying spectrum maneuvers after each onboard system software adjustment.

Once the algorithms have been developed, a limited flight test evaluation of the finalized software should be performed to ensure that all software thresholds have been set appropriately. However, prior to the flight test validation, the final location of the algorithms must be determined. The algorithms can permanently reside in a ground-based computer system, or they can reside on the aircraft as onboard software. There are advantages and disadvantages of each approach, and the best solution can only be determined according to the specific application.

For U.S. Navy applications, and presumably for any operator with a large fleet, it is more advantageous for the software to reside in a centralized ground-based system with all fleet data being sent to this centralized location for regime and fatigue damage accumulation processing. The primary reason for this is to allow for maximum flexibility in the regime recognition and fatigue damage tracking process. Onboard aircraft software updates within the Navy can be costly and slow to be incorporated into all fleet aircraft. And, though the algorithms should be stabilized at the time of fleet introduction, there are various reasons why a software update might be necessary.

For example, the aircraft mission could change, resulting in the need to recognize additional regimes. Another reason for a software update would be due to a manufacturing problem that results in a lower than anticipated strength for a specific lot of components. This would require the recalculation of fatigue damage for all fleet aircraft with that specific component. There are a variety of reasons why unanticipated software updates may be necessary in the long term. As such, a ground-based software set is more efficient to avoid the costly and often slow process of incorporating new onboard system software.

With this approach, the aircraft software for structural monitoring is primarily a data collector that will require few, if any, software updates. The recorded data for each aircraft can then be electronically transferred to one centralized location for processing. This method, in addition to avoiding repeated onboard software updates, also significantly improves the capability to perform data integrity checks of the regime recognition data as well as the final damage assessment that uses that data.

It should be pointed out that this approach of using a centralized ground-processing unit does require a dedicated staff of personnel to process the data. Over the long term, the efficiency of the process should be improved and the number of personnel can be minimized, but it is not anticipated that this process can be 100% automated. A man-in-the-loop will likely be necessary to ensure that the fatigue damage calculations progress appropriately and to ensure that maximum benefit is obtained at the individual aircraft level.

An alternate approach that is possibly more appropriate for a small operator is for the regime recognition software to reside onboard the aircraft. This approach would be appropriate where onboard software updates are manageable, and it is not desirable or possible to maintain dedicated ground-processing personnel. Regimes would be calculated onboard the aircraft, and a conservative damage accumulation calculation could be done in real-time onboard the aircraft. This approach may not allow for the comprehensive data integrity checks that would be possible in ground-based software. Appropriate conservative factors would have to be developed to mitigate this risk. Once these conservative factors are developed and applied, a benefit, though possibly not as significant as in a ground-based system, could be achieved. This would allow for a turn-key damage tracking system without the need for dedicated data processing personnel. This approach might also be appropriate for a multifunctional HUMS system where rotor track and balance is the primary function.

6. CONCLUSIONS.

The core parameters and aircraft-specific parameters that are necessary for reliable regime recognition of spectrum maneuvers have been defined in this report. In addition, parameters that are not necessarily required, but are useful in improving recognition reliability, have also been defined. It was found that monitored parameters should use pre-existing aircraft sensors and data available via the databus whenever possible to avoid dedicated sensors to support structural monitoring only. An assessment of the effect of using a minimal parameter set was performed using data for an SH-60R aircraft. Minimum data rates for regime recognition input parameters have also been established for two military aircraft, the H-60 and V-22. The results, which are summarized in this report, are applicable to commercial utility helicopters and tiltrotor aircraft. The following specific conclusions have been reached.

1. If a reduced parameter set is proposed for a monitoring system, certain aspects of the component damage calculations will likely be missed. In this study, the SH-60R damage tables were reviewed and it was determined that if 14 key parameters are monitored, 66% of the life-limited components of interest could be tracked appropriately. While specific data values established for the reduced parameter set are not necessarily applicable to other aircraft models, the maneuvers that are typically damaging are fairly consistent across platforms. As such, the key parameters for this reduced data set study will likely be applicable to other platforms. When a reduced data set is proposed, the specific impact to accurate component damage calculations must be assessed through review of the aircraft-specific damage rate tables. Appropriate conservative factors must be established for information that is missed due to the use of a reduced data set. Given the damage tables for a specific aircraft model, a similar analysis can be performed and a minimum data set for that model could be established.

2. For commercial utility helicopters and tiltrotor aircraft, the required data rates are highly dependent on the specific input parameter with data-recording rates ranging from 1 to 8 Hz for the military spectrum and from 1 to 6 Hz for the commercial spectrum.

3. For data compression purposes, it was determined that during level flight conditions, data-recording rates for all parameters could be reduced to 1 Hz with the exception of

pilot stick or pedal positions, which must be recorded at 6 Hz to detect control reversals during level flight.

4. Processing of regime recognition algorithms at 8 Hz was found to be sufficient to capture parameter variations, including maximum and minimum input parameter values. For commercial usage spectrum development, it was found that processing of regime recognition algorithms can be performed at 6 Hz.

5. The collection of raw data for postprocessing on the ground is the recommended approach to structural monitoring. This, however, requires a dedicated staff of personnel to process the data over the long term. Where that is not possible, onboard processing can provide a limited benefit. However, a significantly higher risk of erroneous results and data integrity issues may arise as a result. Conservative factors must be applied to counter this risk.

APPENDIX A—TYPICAL REGIMES/FLIGHT MANEUVERS TO BE IDENTIFIED

In this report, structural usage monitoring refers to the process of recognizing the flight regime flown by an individual aircraft at a given time. The measured usage spectrum for any given aircraft can then be mapped to particular components on that aircraft. Components that are used less severely than previously assumed could see some beneficial life extension. Likewise, components flown more severely than previously assumed could be removed and replaced early, thus improving flight safety. A listing of flight regimes applicable to commercial aircraft that can be identified by these structural usage monitoring systems is listed as follows.

I. GROUND CONDITIONS

- A. ROTOR START
- B. ROTOR SHUTDOWN
- C. TAXI
- D. TAXI TURNS

II. IN-GROUND EFFECT MANEUVERS

- A. TAKEOFF
    - 1. NORMAL
    - 2. JUMP
- B. HOVERING
    - 1. STEADY
    - 2. TURNS
        - A. LEFT
        - B. RIGHT
    - 3. CONTROL REVERSAL
        - A. FORE/AFT
        - B. LATERAL
        - C. PEDAL
- C. SIDEWARD FLIGHT
    - 1. LEFT
    - 2. RIGHT
- D. REARWARD FLIGHT
- E. NORMAL ACCELERATION
- F. DECELERATION
    - 1. NORMAL
    - 2. QUICK STOP
- G. NORMAL LANDING

III. FORWARD LEVEL FLT

<u>AIRSPEED</u>

- A. 0.5VH
- B. 0.6VH
- C. 0.7VH
- D. 0.SVH
- E. 0.9VH

F. 1.0VH

IV. OUT-OF-GROUND EFFECT MANEUVERS
  A. FULL POWER CLIMB
    1. TWIN ENGINE
    2. SINGLE ENGINE
  B MAX RATE ACCELERATION
  C. MAX RATE DECELERATION
  D. LEFT AND RIGHT STEADY TURNS
    1. DESCENDING
    2. LEVEL
    3. CLIMBING
  E. CONTROL REVERSAL IN LEVEL FLIGHT
    1. FORE/AFT
    2. LATERAL
    3. PEDAL
  F. SIDESLIP
    1. TO THE LEFT
    2. TO THE RIGHT
  G. PARTIAL POWER DESCENT
    1. TWIN ENGINE
    2. SINGLE ENGINE
  H. DIVES
  I. PULL-UPS
    1. LEFT ROLLING
    2. RIGHT ROLLING
    3. SYMMETRICAL
  J. AUTOROTATION
    1. STABILIZED
    2. AUTO TURNS
    3. FULL AUTO LANDING

APPENDIX B—MAXIMUM ERROR TRENDS WITH DATA RATE FOR COMMERCIAL SPECTRUM DATA

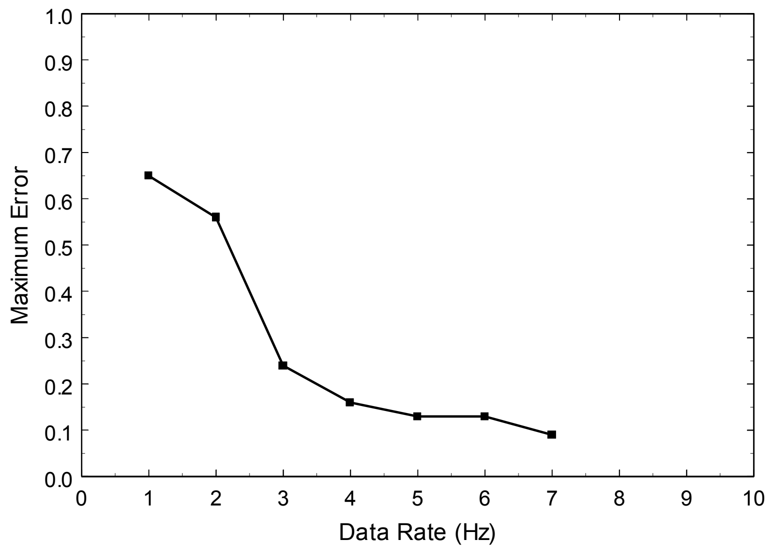

FIGURE B-1. MAXIMUM ERROR VERSUS DATA RATE FOR VERTICAL ACCELERATION (g's)

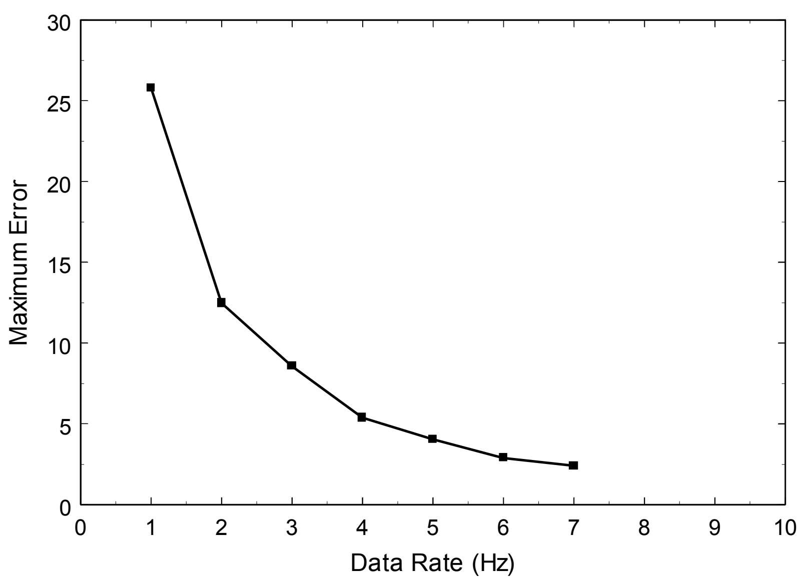

FIGURE B-2. MAXIMUM ERROR VERSUS DATA RATE FOR ENGINE TORQUE (%)

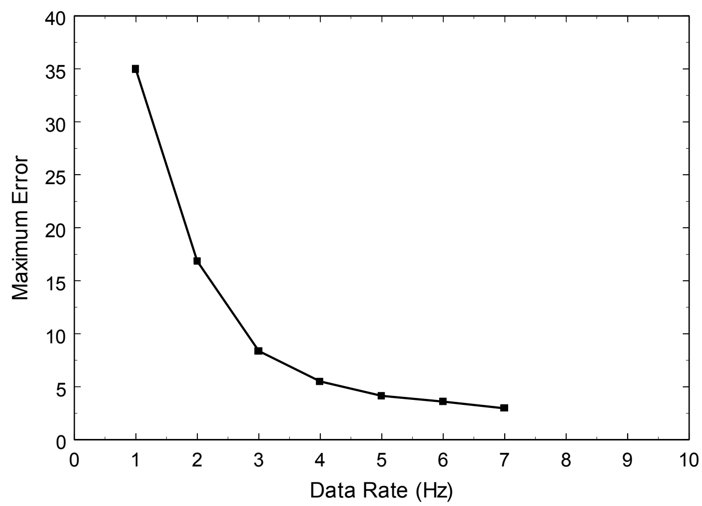

FIGURE B-3. MAXIMUM ERROR VERSUS DATA RATE FOR ROLL RATE (deg/sec)

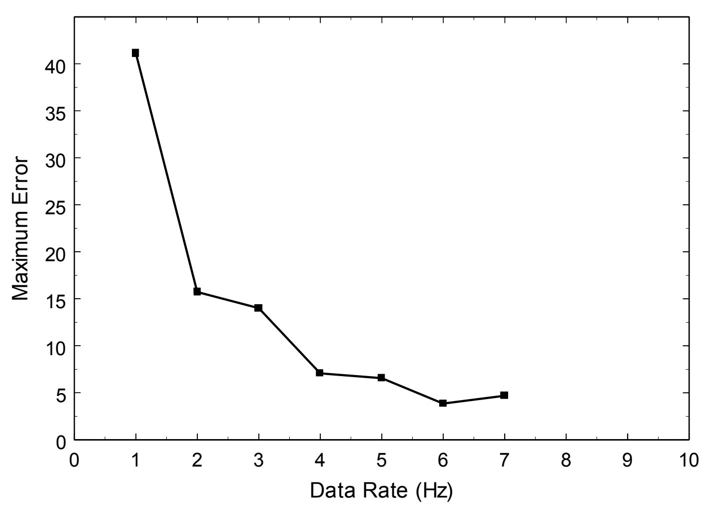

FIGURE B-4. MAXIMUM ERROR VERSUS DATA RATE FOR LATERAL STICK POSITION (%)

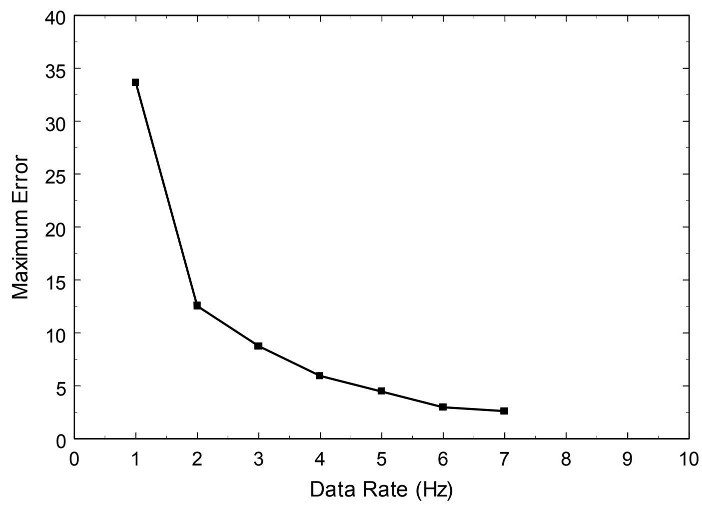

FIGURE B-5. MAXIMUM ERROR VERSUS DATA RATE FOR PEDAL POSITION (%)

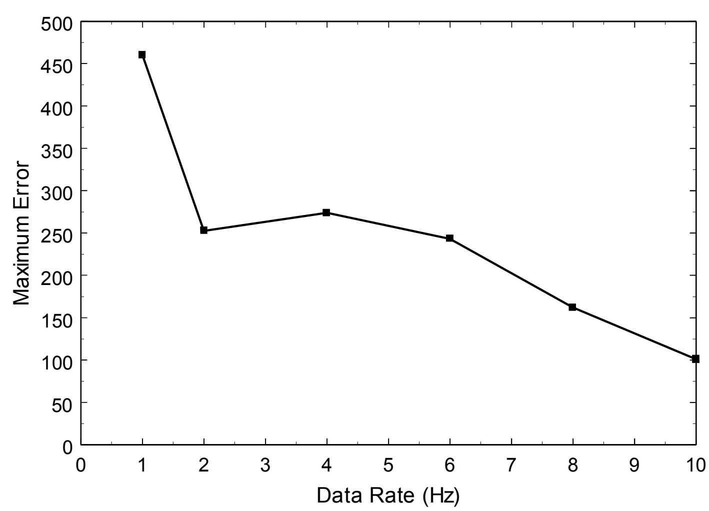

FIGURE B-6. MAXIMUM ERROR VERSUS DATA RATE FOR
VERTICAL VELOCITY (ft/min)

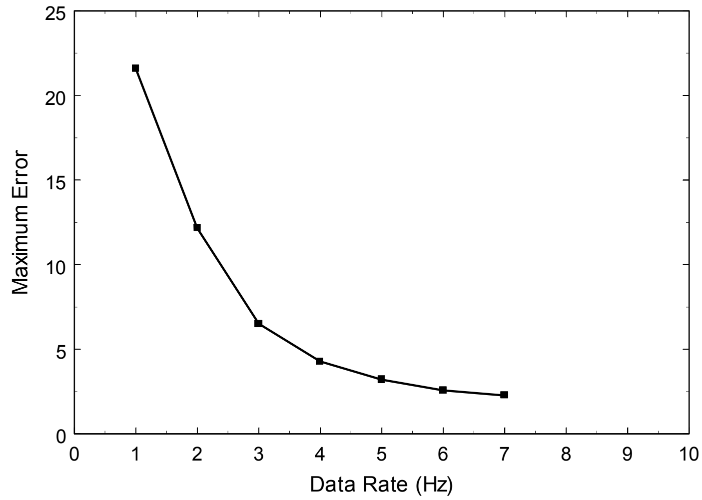

FIGURE B-7. MAXIMUM ERROR VERSUS DATA RATE FOR LONGITUDINAL STICK POSITION (%)

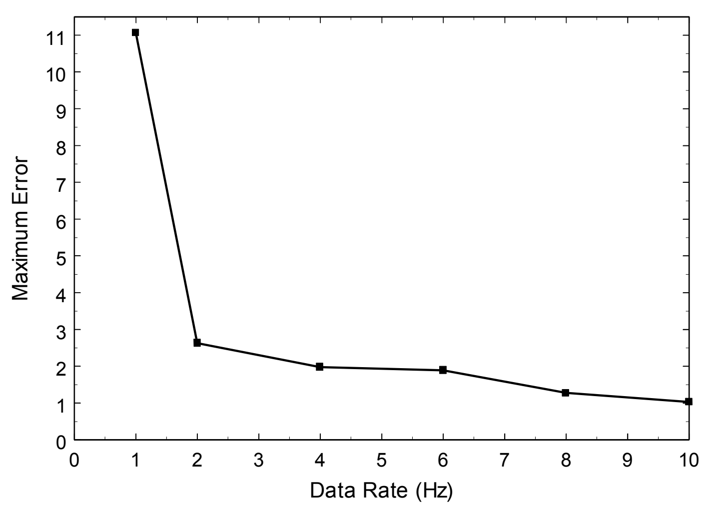

FIGURE B-8. MAXIMUM ERROR VERSUS DATA RATE FOR ROLL ATTITUDE (deg)

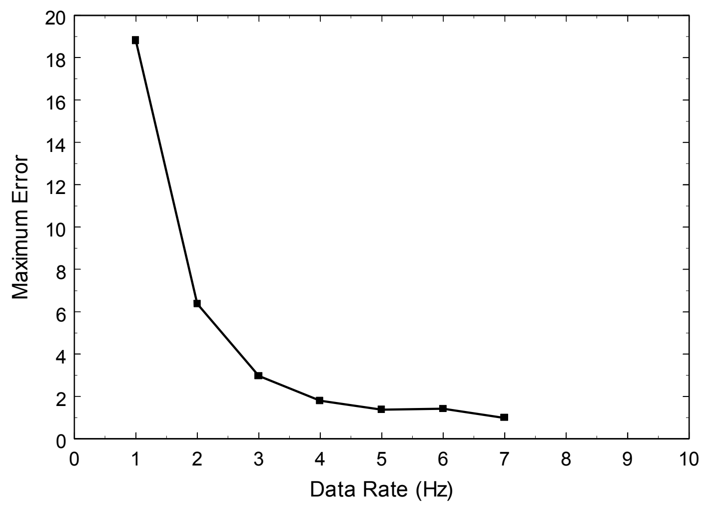

FIGURE B-9. MAXIMUM ERROR VERSUS DATA RATE FOR PITCH RATE (deg/sec)

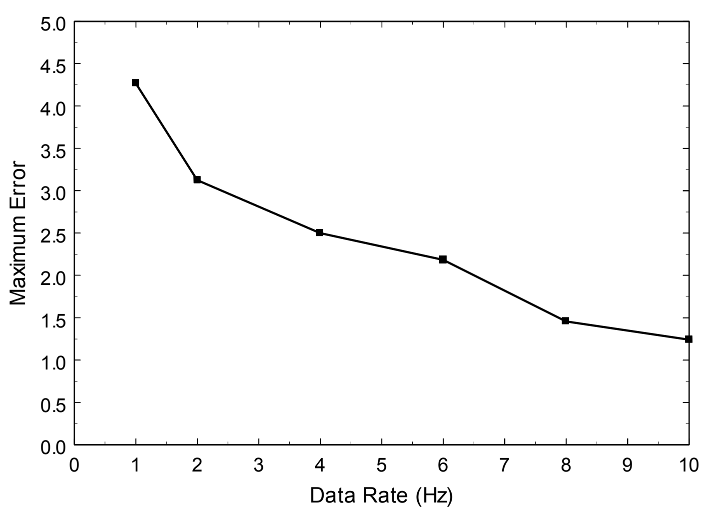

FIGURE B-10. MAXIMUM ERROR VERSUS DATA RATE FOR YAW RATE (deg/sec)

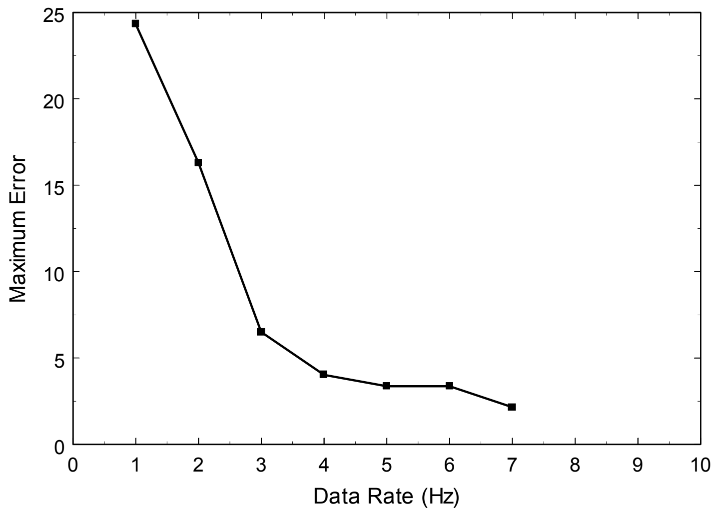

FIGURE B-11. MAXIMUM ERROR VERSUS DATA RATE FOR COLLECTIVE STICK POSITION (%)

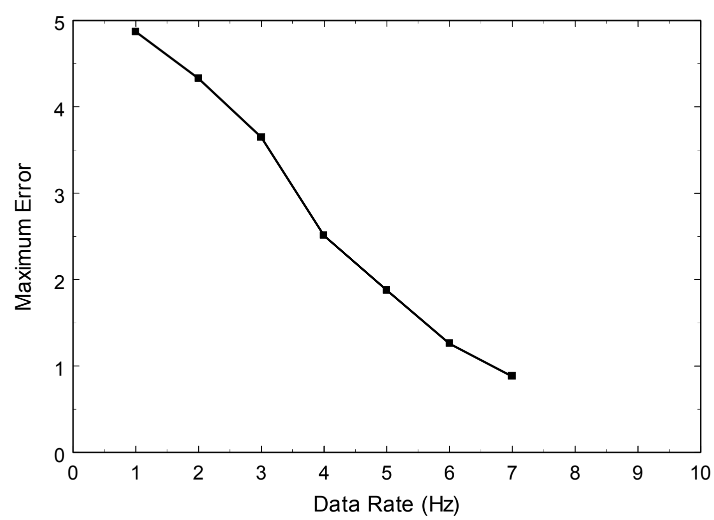

FIGURE B-12. MAXIMUM ERROR VERSUS DATA RATE FOR AIRSPEED (kt)

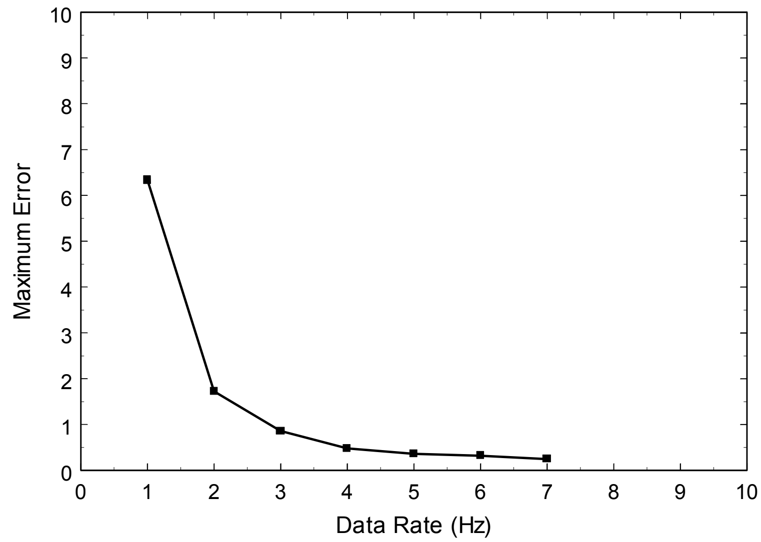

FIGURE B-13. MAXIMUM ERROR VERSUS DATA RATE FOR PITCH ATTITUDE (deg)

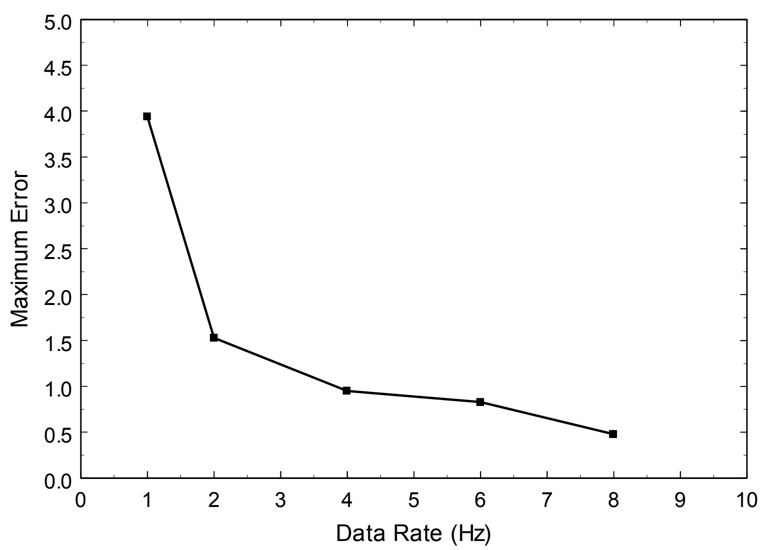

FIGURE B-14. MAXIMUM ERROR VERSUS DATA RATE FOR ROTOR SPEED (%)